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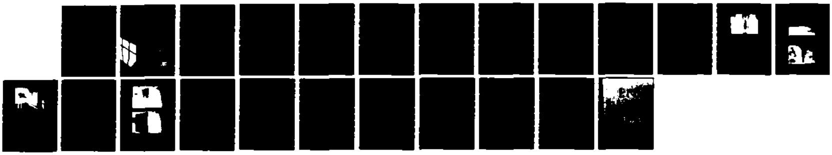

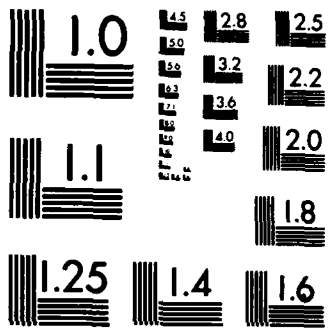

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TECHNICAL REPORT M-332
August 1983
(EMP/EMI Shielding Criteria and Hardness Testing)

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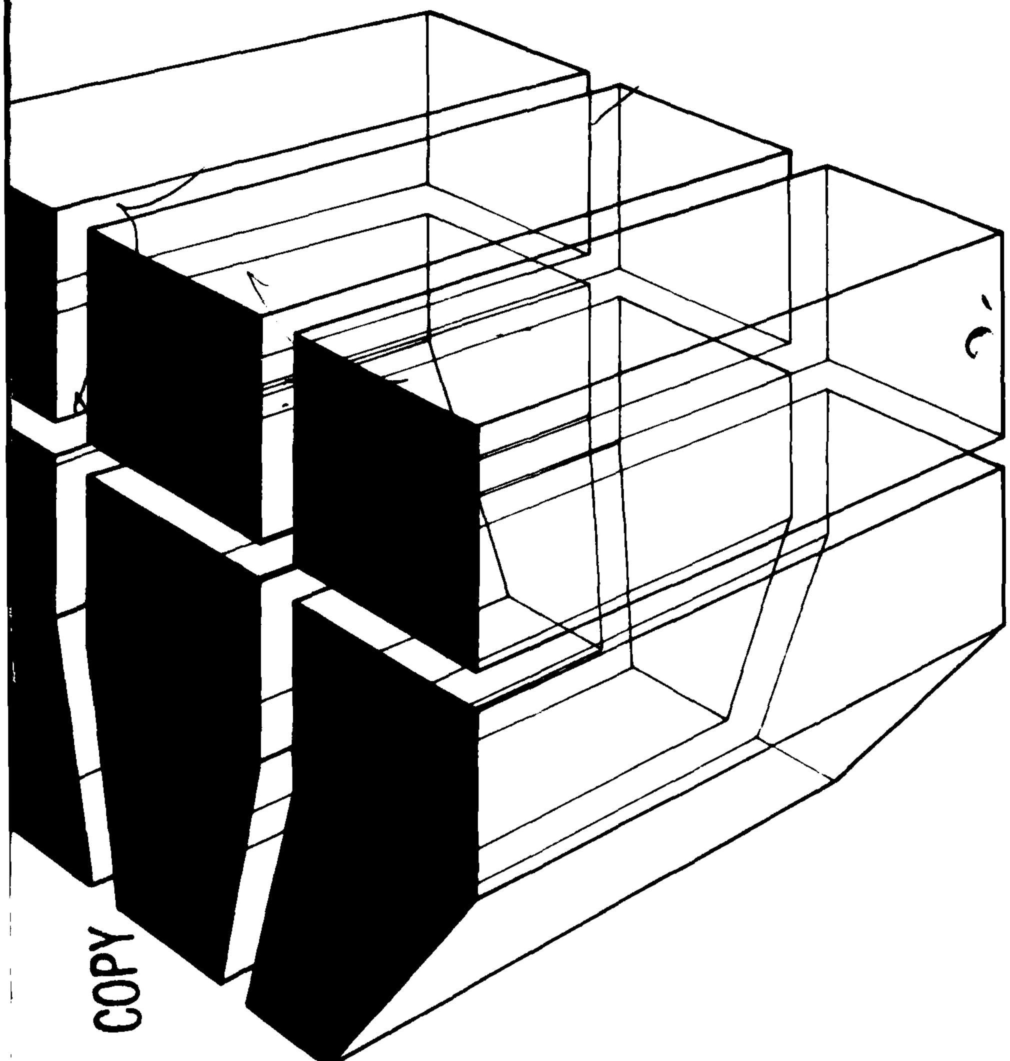
ELECTROMAGNETIC SHIELDING OF FULL-SIZED STRUCTURES BY METAL ARC SPRAYING



by
Paul Nielsen

CERL

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This report describes a study to determine the feasibility of arc spraying metal onto a room-sized structure to provide economical electromagnetic shielding.

The study concluded that shielding can be significantly upgraded by arc spraying over the seams of existing modular shielded construction. Structural shielding can also be supplied by arc spraying metal onto standard construction materials.

FOREWORD

This work was conducted for the Directorate of Engineering and Construction, Office of the Chief of Engineers (OCE) under Project 4AT62719AT40, "Mobility and Weapons Effect Technology"; Task A, "Weapons Effect"; Work Unit 022, "EMP EMI Shielding Criteria and Hardness Testing." The OCE Technical Monitor was Mr. P. Brake, DAEN-ECE-E.

The work was performed by the Engineering and Materials (EM) Division of the U.S. Army Construction Engineering Research Laboratory (CERL). Dr. Robert Quattrone is Chief of CERL-EM.

COL Louis J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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ELECTROMAGNETIC SHIELDING OF FULL-SIZED STRUCTURES BY METAL-ARC SPRAYING

1 INTRODUCTION

Background

It may be necessary to electromagnetically shield certain military structures to (1) protect sensitive electronics from external interference, (2) prevent emanations from equipment processing classified information from being compromised, or (3) provide electromagnetic pulse (EMP) protection. Conventional fixed facility shielding construction systems are usually either welded sheet metal or modular bolt-together panels. These shielded rooms may be free-standing or part of the basic construction of the host building. Unfortunately, conventional shielding construction technology is relatively expensive and not readily applicable to the retrofit of existing structures.

Metal-arc spraying is an accepted technology for shielding the plastic housings of electronic equipment. Plastic is now commonly used for such equipment cases or housings because it is less expensive than metal, although metal has significant inherent electromagnetic shielding properties. A relatively inexpensive way to impart the same shielding properties to plastic housings is to arc spray a thin conducting metal coat onto the plastic. Metal arc spraying of room-sized structures is a logical extension of this successful technology.

Earlier studies by the U.S. Army Construction Engineering Research Laboratory (CERL) on molten-metal coating for electromagnetic shielding used sample panels which could be bolted over a 2- by 4-ft (0.6- × 1.2-m) window in CERL's high-performance shielded room.[1] Those samples consisted of a variety of metals sprayed onto typical construction materials. This report describes a study to determine the feasibility of arc spraying room-sized structures.

[1]Paul Nielsen, *Arc-Sprayed Metals for Structural Electromagnetic Shielding*, Technical Report M-316/ADA117673 (U.S. Army Construction Engineering Research Laboratory [CERL], June 1982); and *Study of EMI/RFI Shielding of Tactical Shelters*, Air Force Technical Manual, ESL-TR-80-24 (Department of the Air Force, 1980).

Objective

The objective of this study was to determine the feasibility of arc spraying a room-sized structure to provide economical electromagnetic shielding.

Approach

1. Test 1: shielding upgrading of an existing modular structure. An existing modular shielded room which had been subjected to high humidity conditions was modified by applying foil tape over the seams and arc spraying seam areas with zinc. The degree of shielding improvement was measured.

2. Test 2: arc spraying of a drywall room. A free-standing room made using conventional drywall construction techniques was wallpapered with copper foil. The electromagnetic shielding of the room was measured as a "benchmark" and the foil removed. The room was then arc sprayed with zinc and retested.

Mode of Technology Transfer

It is recommended that the results of this study be used to update Army Technical Manual 5-855-5, *Nuclear Electromagnetic Pulse (NEMP) Protection* (Department of the Army, February 1974).

2 OVERVIEW: PROCESS AND APPLICATIONS

Arc spraying is a technique for depositing molten metal droplets onto metallic or nonmetallic substrates. In the arc spraying process, an electric arc is drawn between two wire electrodes. The arc melts the wires and the molten metal is blown onto the surface being sprayed by a high-velocity compressed airstream directed through the arc. Droplet size and the resulting quality of the deposited metal layer is a function of the wire feed and airflow rates, pressure, and arc voltage. Thus, some operator skill is required to get a satisfactory surface. In general, a sprayed coating should be smooth, have uniform thickness, and not be porous.

Equipment

A typical arc-spraying system consists of:

1. A DC power supply to convert a readily available AC source into the DC required for an electric arc. This unit should have an ammeter and

voltmeter to facilitate adjustments. The output voltage should be continuously variable, so the unit can be adjusted to provide the best spraying conditions for each spray material.

2. A control unit.

3. A spray gun (with cables and an air hose connected to the control unit) capable of continually delivering air at about 35 cfm (1 m^3/min) at about 100 psi (689 kPa).

Applications

The following are practical applications of metal arc spray technology to electromagnetic shielding:*

Metallizing Mating Surfaces

1. Temporary openings. Doors, access panels, and similar temporary openings make it difficult to maintain the shielding effectiveness of shielded enclosures, because corroded or contaminated mating surfaces degrade shielding performance. Arc or flame spraying mating surfaces with corrosion-resistant, electrically conductive coatings can help prevent this degradation. Zinc and tin are good for interior applications, since these metals have low melting points and are soft. The low melting point means these metals are easy to apply by spraying; their malleability is an advantage because they deform slightly under relatively low pressure, providing good electrical contact.

2. Permanent construction. Typical bolt-together modular shielded construction deteriorates with age, mainly because the mating surfaces corrode. Arc spraying these surfaces with a soft, low-melting-point metal before construction may greatly reduce such corrosion, at only a slight increase in initial cost.

Upgraded Existing Modular Shielded Construction

Modular shielded construction usually has 4 × 8 ft (1.2 × 2.4 m) metal or metal-clad plywood sheets joined by specially designed bolted seam systems. Although these structures initially shield well, they typically degrade with time. The main cause of this degradation is an increase in electrical resistance at the seams, caused by factors like surface corrosion and loosened fasteners. The usual way to rehabilitate a degraded structure is to break it down, clean all its mating surfaces, and reassemble it. However, molten metal spraying can upgrade degraded structures much more easily: the seam areas are sandblasted clean and the metal is arc sprayed over the seam. The metal deposit must be thick enough to cover any cracks between the joining metal parts.

Providing a Shielding "Membrane"

A shielding "membrane" can be produced by arc spraying a metal layer on all surfaces of a conventionally constructed room. The following are important considerations for such an approach:

1. In general, thicker layers will have proportionally greater shielding.

2. Shielding may be increased by using multiple layers of sprayed metal. One way to get multiple layers is to arc spray both sides of the wall.

3. A reasonable rate of coverage for a hand-held arc-spray gun is about 20 sq ft/hr (0.005 m^2/s).

4. In general, a shielding effectiveness of 35 to 75 decibels (dB) can be expected from an estimated thickness of 5 to 7 mils of zinc on drywall. Figure 1 shows typical shielding effectiveness obtained from 2 × 4 ft (0.6 × 1.2 m) test samples.

5. Penetrations such as doors, air vents, and electrical filters should be handled the same as conventional shielded construction, except for the interfacing with the arc-sprayed coating. A recommended method is to surround the item with a metal "lip" about 1-in. (24.5-mm) wide. This "lip" should be mounted flush with the structure wall to be sprayed. Electrical filters should be mounted on metal plates similarly interfaced with the arc-sprayed wall.

6. Floors can best be shielded by using a 22- to 26-gage galvanized sheet steel as a protected subfloor. Seams should be soldered.

7. Care must be taken to prevent unbonded nails, fasteners, or other conductors from passing through the shielding layer. Such items can act as antennas and greatly reduce shielding effectiveness.

Techniques

Surface Treatment

1. Surfaces to be arc sprayed with metal should be clean, dust free, and unpainted. Low-melting-point metals like tin or zinc will adhere well to concrete, drywall, masonite, plywood, and similar materials.

*These applications are based on the results of previous work by CERL and the research reported here.

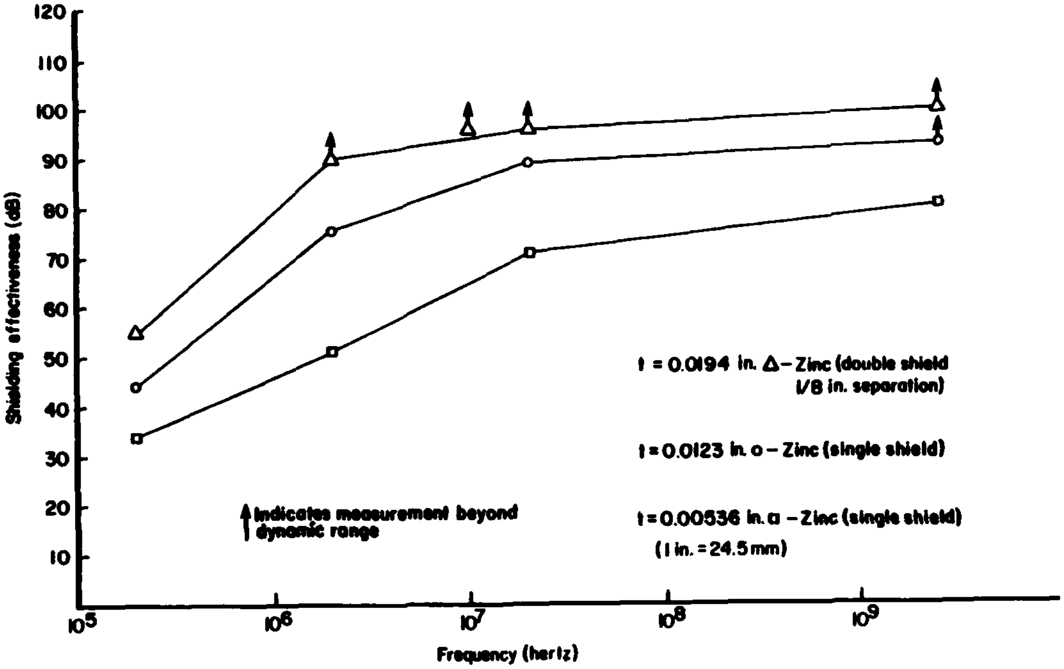

Figure 1. Shielding effectiveness of arc-sprayed zinc.

Materials like concrete must have all loose particles removed. For best adhesion, metal surfaces should also be roughened, preferably by sandblasting.

2. Since the deposited arc-sprayed metal has little physical strength, the base material should not be subject to movement or cracking, which could harm the shielding properties of the metal layer.

3. If the substrate is flammable, the operator must be careful not to hold the spray jet in one place long enough to char or ignite the base material.

Coatings

Electromagnetic shielding results from a material's electrical conductivity and/or magnetic permeability, so good conductors and high permeability materials produce the most shielding. Iron and steel are common high-permeability materials, but a high melting point and high rate of oxidation limit their adhesion to typical materials. Adhesion of these metals can be improved by first arc spraying the surface with a low-melting-point metal like zinc. A coating of zinc by itself is sufficient for low- to medium-shielding requirements; the coating should be uniform and it should be at least 5 to 10 mils thick. The arc should be adjusted for a relatively small particle size.

Safety Considerations

Operator and bystander safety are vitally important and must be considered in the planning phase. The American Welding Society (AWS) publication AWS C2.1-73, *Recommended Practices for Thermal Spraying,* and the operator's manual for the equipment should be consulted before beginning operations. Safety considerations are generally the same as those for welding inside structures and require that the operator wear a hood and use supplied air during spraying. Adequate ventilation is also essential, since some metals produce toxic fumes or other byproducts. Good ventilation and dust extraction will also help prevent the coating from being contaminated. The operator must use filters to protect him or herself from ultraviolet radiation; bystanders should be protected, where possible, by a portable screen.

3 TEST DESCRIPTIONS AND DISCUSSION

Background

Earlier CERL tests of samples of arc-sprayed metals on typical construction materials determined the feasibility of using arc-spray technology for electromagnetic shielding. The samples were sized to cover a 2 × 4 ft (0.6 × 1.2 m) window in a high-performance shielded room. These tests also determined material properties, including:

1. Bond strength between the deposited metal and the base material.

2. The density of the deposited metal.

3. Electrical conductivity of the sprayed metal.

Electron microscope pictures were taken to characterize the physical appearance of the metal. Shielding tests of a simulated buckled seam repaired with arc spraying were also made. These earlier test results indicated arc spraying metal on conventional construction materials will provide significant electromagnetic shielding.[2]

Test Process and Equipment

CERL's arc-spray system consists of:

1. A 200-A, DC plasma power supply unit with an operating range of 230 to 460 V, 60 Hz. It had an ammeter and voltmeter, and its output voltage was continuously variable so it could be adjusted to provide the best spraying conditions for each spray material.

2. A control unit which had a spray air gage, a wire feed pressure gage, and the system operating controls.

3. A spray gun (with cables) and an air hose connected to the control unit.

The equipment was manufactured by Tafa Metalligation Inc., Bow (Concord), NH 03301.

The system requires an external air supply of at least 100 psi (689 kPa). The maximum volume of air needed is 35 to 40 cu ft/min (0.06 to 0.02 m^3/s).

Tests on Upgrading of Existing Modular Shielded Construction

Typical modular shielded construction consists of sheet metal or sheet-metal-clad plywood. A standard dimension is 4 by 8 ft (1.2 × 2.4 m). The sheets are bolted together by any of a variety of techniques. Normal aging tends to degrade the shielding performance of most such facilities.[3] These degrading effects are accelerated in adverse environments. The main factor influencing this degradation is an increase in contact resistance at the seam area. An accepted technique for refurbishing these structures is to dismantle the room, clean the mating surfaces, and reassemble the room. Results of an earlier study on a simulated buckled seam showed that arc spraying a layer of metal over the seam significantly improves electromagnetic shielding.[4]

For this study, the ceiling and floor seams of a small shielded room which had been subjected to severe environmental aging effects were dismantled, cleaned, and reassembled.

The structure was then tested using the procedures of Military Standard 285, National Security Agency (NSA) Specification 65-5, and Institute of Electrical and Electronics Engineers (IEEE) Practice 299.[5] The tests were essentially low-frequency loop (magnetic field) at 100 kHz, dipole (plane wave) at 400 MHz, and microwave at 2.4 GHz.

The test seam areas were then cleaned without disassembling and taped with 3M copper foil tape No. 1181 (Figure 2). This tape has a conductive adhesive. The seams were then tested again. Figure 3 shows the test points.

The tape was removed and the seams were sand-blasted without dismantling and arc sprayed with zinc (Figures 4 through 6). Another test was conducted (Figure 5).

All test results are listed in Table 1.

Differences between foil tape and no seam covering, between arc-sprayed zinc and no seam covering,

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[2]Paul Nielsen, *Arc-Sprayed Metals for Structural Electromagnetic Shielding*, Technical Report M-316/ADA117673 (CERL, June 1982).

[3]R. G. McCormack, *EMI/RFI Shielding Effectiveness Evaluation of Bolt-Together Shielded Rooms in Long-Term Aging*, Technical Report M-296/ADA102754 (CERL, June 1981).

[4]Paul Nielsen, Technical Report M-316 (CERL, June 1982).

[5]*Military Standard Attenuation Measurements for Enclosures, Electromagnetic Shielding for Electronic Test Purposes, Method of*, MIL-STD-285 (Department of Defense, 25 June 1956); *Proposed IEEE Recommended Practice for Measurement of Shieldi[illegible] fectiveness of High-Performance Shielding Enclosures*, 299 [illegible]itute of Electrical and Electronics Engineers [IEEE], June 1969); and P. R. Trybus, *National Security Agency Specification for R-F Shielded Enclosures for Communications Equipment: General Specification*, NSA 65-6 (National Security Agency, 30 October 1964).

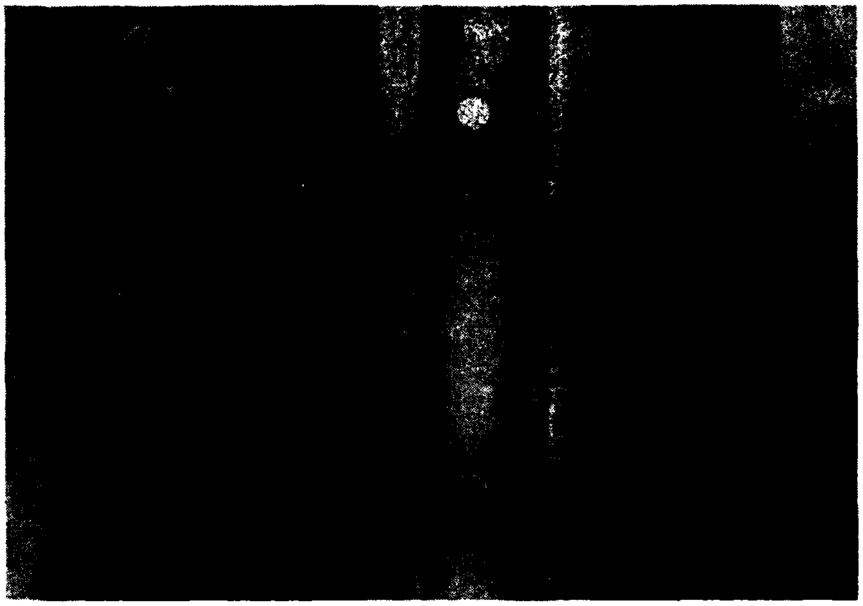

Figure 2. Test 1: test seam areas covered with 3M copper foil tape No. 1181.

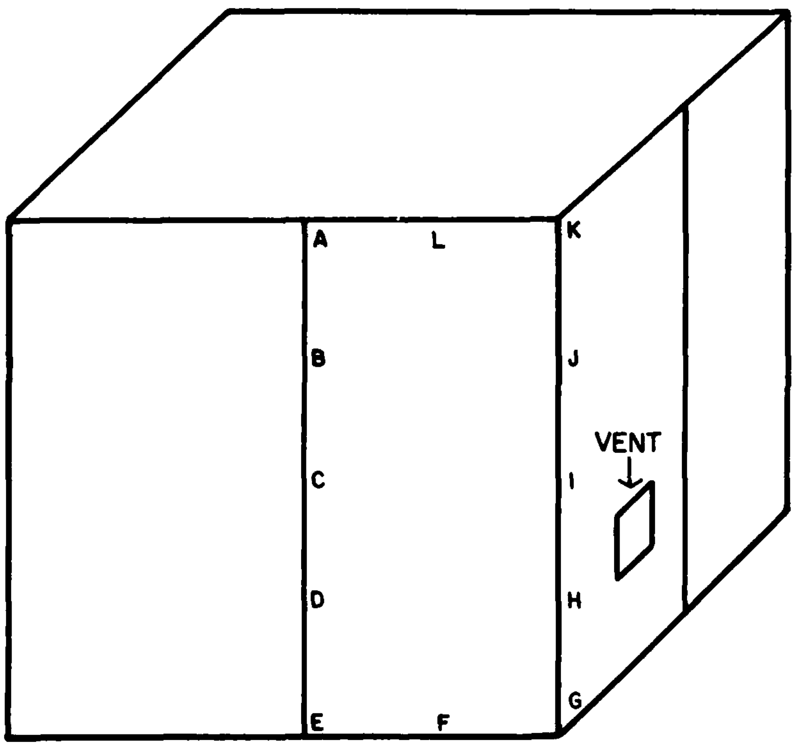

Figure 3. Test points for modular structure seam treatment.

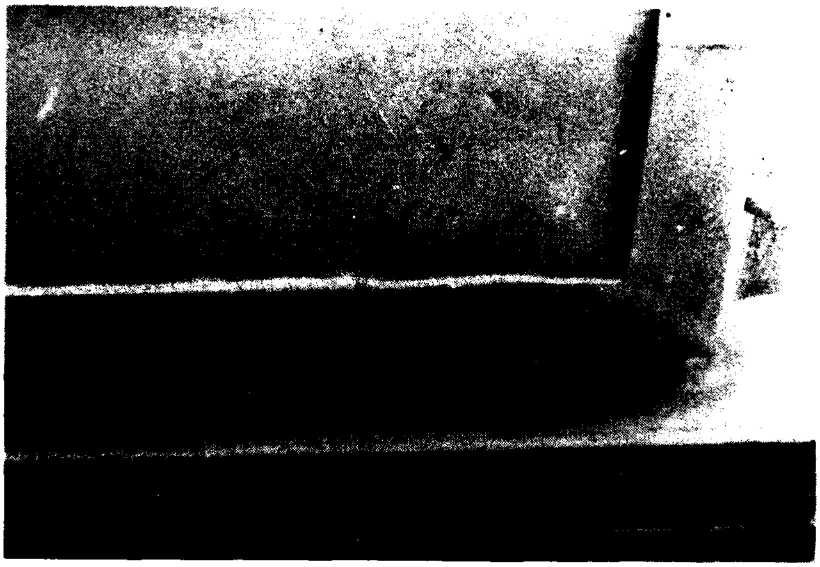

Figure 4. Test 1: arc-sprayed seam.

Figure 5. Test 1: arc spraying taped seam.

Figure 6. Test 1: testing arc-sprayed taped seam.

and between arc-sprayed zinc and foil tape were statistically analyzed. For all three frequencies:

1. The foil tape produced significantly higher shielding than the no seam covering.

2. The arc-sprayed zinc produced significantly higher shielding than the no seam covering.

3. The arc-sprayed zinc produced significantly higher shielding than the foil tape.

Tests were significant at the 99 percent confidence level. Although the results show a significant increase in shielding effectiveness, they must be regarded as the minimum improvement. This is because not all the structure's seams were upgraded, and some of the other seams may have leaked.

Sheet Rock (Drywall) Room

To test ways to shield a full-sized room, CERL built an 8 × 8 × 8 ft (2.4 × 2.4 × 2.4 m) frame room with a drywall (sheetrock) wall (Figure 7). Conventional construction techniques were used, except the drywall surface was on the outside (Figure 8). Both the floor and ceiling were shielded with soldered galvanized sheet steel. A 2-in. (51-mm) lip was provided around the edge of each floor and ceiling panel. (These panels are visible in Figure 8.) A personnel and equipment entry was mounted on a metal framework in one wall. The framework was made of channel iron; the outer surface was arc sprayed with zinc. A cover was bolted in place so the shielding tests could be conducted. A honeycomb wave-guide, below-cutoff air filter was installed on another wall of the structure to provide ventilation. Electrical power was brought into the room through an electrical filter mounted on the roof.

The structure's walls were then "papered" with a 1-mil copper foil for the baseline shielding effectiveness tests. The seams plus the roof and floor attachments were taped with 3M copper foil No. 1181. This tape had a conductive adhesive.

After the baseline tests, the copper foil was removed and the structure's four walls were arc sprayed with zinc. The weight of the zinc applied to the structure was recorded by noting the weight of the zinc wire rolls before and after arc spraying. An estimate for the thickness of the arc-sprayed layer was made using the weight and the total surface area sprayed. The calculated thickness was about 5 to 6 mils.

The shielding tests of the arc-sprayed room were conducted at the points shown in Figure 9. Test results are listed in Table 2.

The test results at 400 MHz and 2.4 GHz indicate

Table 1
Shielding Effectiveness of Treated Seams on a Modular Shielded Room

Frequency = 100 kHz

Test Point	Measured Shielding Effectiveness (dB) No Seam Covering	Foil Tape	Arc-Sprayed Zinc
A	72	77	90
B	82	80	114
C	58	84	118+
D	66	53	96
E	44	50	62
F	37	53	52
G	28	40	38
H	42	58	71
I	47	68	107
J	66	84	116
K	64	80	88
L	90	81	100
Average for all points	58	67	88

Frequency = 400 MHz

Test Point	Measured Shielding Effectiveness (dB) No Seam Covering	Foil Tape	Arc-Sprayed Zinc
A	50	82	77
B	50	74	78
C	48	80	73
D	50	72	84
E	42	70	94
F	36	74	92
G	48	86	76
H	50	74	67
I	54	64	62
J	52	62	65
K	46	64	67
L	38	66	72
Average	47	72	76

Frequency = 2.4 GHz

Test Point	Measured Shielding Effectiveness (dB) No Seam Covering	Foil Tape	Arc-Sprayed Zinc
A	50	69	74
B	68	69	86
C	62	72	90
D	72	75	90
E	57	69	82
F	67	72	90
G	57	62	68
H	65	71	82
I	62	70	86
J	62	61	90
K	57	67	82
L	62	59	82
Average	62	68	83.5

Figure 7. Test 2: drywall (rockwall) room.

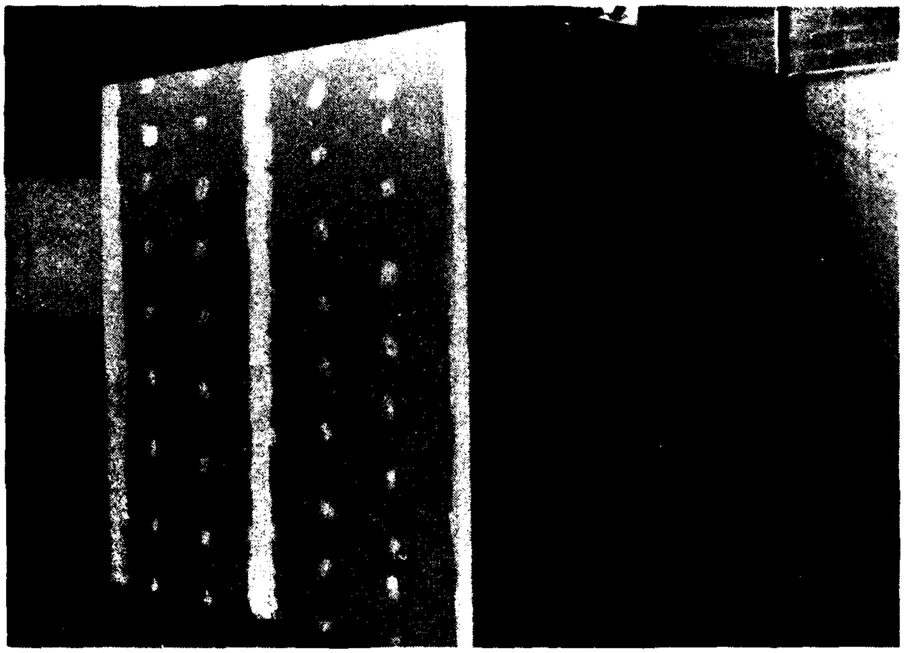

Figure 8. Test 2: drywall location.

an apparent leak at the air vent. This air vent was mounted on the outside of the structure with wood screws after the room was arc sprayed. An RFI mesh gasket is attached to the wall side of the vent.

A leak anywhere in the room at these frequencies will influence the shielding readings everywhere in the room. Most leaks at these frequencies are caused by aperatures. Thus, if the hardware interface problems can be resolved, it is likely that the shielding performance at high frequencies can be significantly increased.

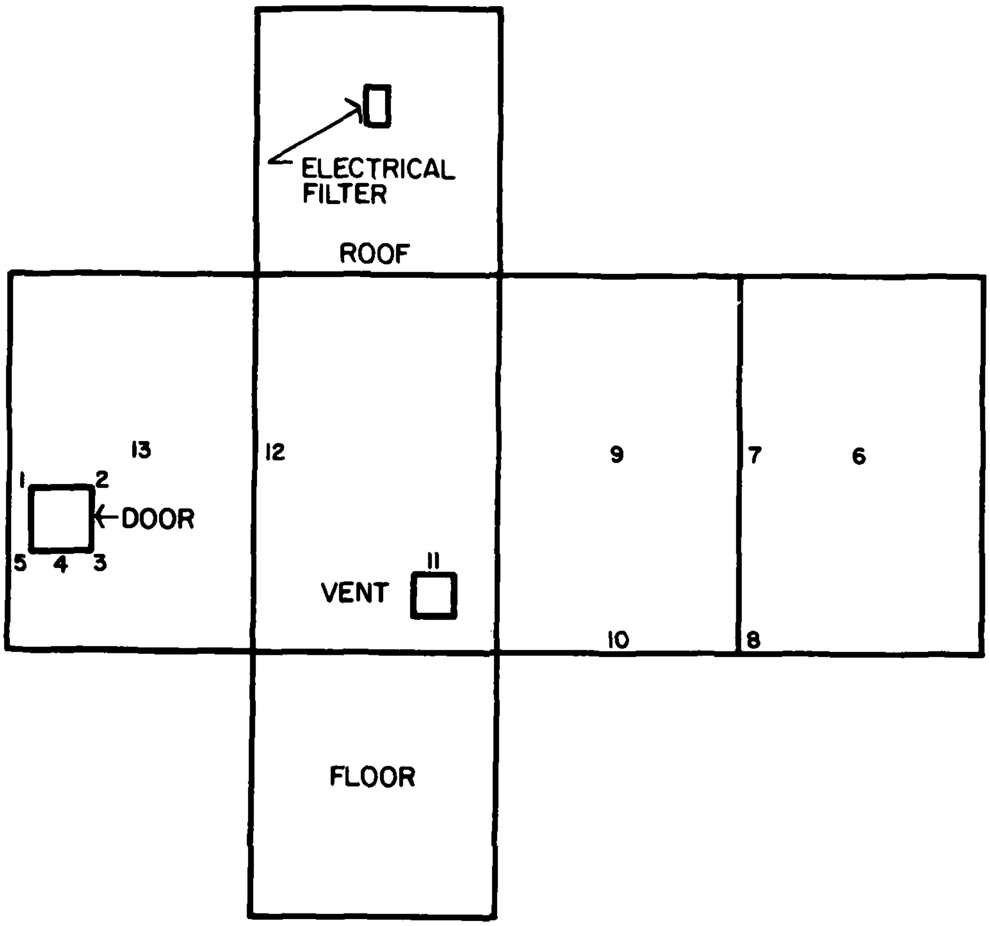

Figure 9. Test 2: zinc arc-sprayed room, shielding effectiveness test points.

Table 2
Shielding Effectiveness of Zinc Arc-Sprayed Room

Location	Shielding Effectiveness (dB, average of points listed) 100 kHz	1 MHz	10 MHz	400 MHz	2.4 GHz
Door Points 1-5	32	35	45.6	50.5	44.6
Middle Wall Points 6, 9, 13	35	51	71.7	52.7	62
Vertical Corner Points 7, 12	34.5	51.5	75	39	66.5
Vent Point 11	35	40	44	40	34
Floor Interface Points 8, 10	36	51.5	71.5	44	38.5
Average without Door and Vent	35	51	73	46	54

Sniffer Tests

An alternate technique for characterizing the performance of a shielded structure is to use a shielded enclosure leak detection system or "sniffer." The shielded room is externally excited at about 100 kHz. An operator using a hand-held receiver with a probe antenna then searches the inside of the room to detect shielding defects. Normally the current will flow on the outside surface of the structure. Electrical defects interrupt the uniform surface current flow and can allow a signal to enter the structure at that point. This test technique differs from most other shielding tests in that the test current is directly injected onto the structure while current is induced on the structure from antennas with the radiated field tests. Thus, no shielding due to reflection losses is accounted for with the "sniffer." No correlation exists with the number read on the "sniffer" meter and the radiated shielding effectiveness test number, although industry experience has shown that a structure performing well in a "sniffer" test will perform well in most other tests.

The results of the "sniffer" tests on the copper foil "papered room" and the zinc arc spray room are given in Figures 10, 11, and 12. In general, the readings are very high for shielded structures. One reason for this can be deduced from examining the skin depth. One skin depth (δ) is the depth into a conductor at which a surface current is reduced to $1/e$ (attenuated by about 8 dB) of its surface value. The skin depth concept assumes a uniform conductor microstructure. This is not quite true for thin layers of arc-sprayed metals, but the analysis is still reasonably valid.

The formula for skin depth (δ) in conductors is:

$$\delta = \frac{1}{\sqrt{\pi \mu \sigma f}}$$

where μ = the magnetic permeability of the material for most nonferromagnetic materials $\mu = 4\ \pi \times 10^{-7}$ henry/m or $4\ \pi \times 10^{-10}$ henry/mm

σ = the electrical conductivity of the material

f = the frequency of interest.

Using the experimentally determined value of 4.33 $\times 10^4$ mho/cm or 4.33×10^3 mho/mm and a relative permeability of 1 for arc-sprayed zinc and a frequency of 100 kHz, a value of 0.76 mm or about 30 mils is found for the skin depth.

For copper using the bulk conductivity of 5.8×10^4 mho/mm, the calculated skin depth is about 0.21 mm or about 8 mils.

Thus, both the arc-sprayed zinc and the copper foil used in this study are considerably less than a skin depth thick, with an estimated thickness of 5 to 6 mils for the zinc and a 1-mil thickness for the copper. It can therefore be concluded that most of the shielding at this frequency will result from reflection losses. Absorption losses will be negligible. In addition, it appears that the "sniffer" test is not useful in determining the shielding performance of very thin shields.

4 CONCLUSIONS

This study investigated applications of metal arc spray technology to the electromagnetic shielding of full-scale structures. Results indicate that:

1. Shielding can be significantly upgraded by arc spraying over the seams of existing modular shielded construction. The cost of upgrading by arc spraying can be significantly less than that of the conventional technique of dismantling the room, cleaning its seams, then reassembling it.

2. Structural shielding can be supplied by arc spraying metal onto standard construction materials. Arc-sprayed metals will adhere well to most construction materials if the materials are clean and free of loose particles. An additional requirement for good shielding is a stable substrate (no cracks or shifting). Zinc on drywall was used for this study, but there is no reason to believe that other metals will not also be satisfactory.

4. The degree of shielding obtained with CERL's experimental structure was such that it would be rated as a low-to-medium performance room (about 35 dB at 100 kHz to about 75 dB at 400 MHz).

5. The shielding obtained by using a copper foil joined by a foil-backed tape with conductive adhesive was nearly the same as that obtained from the arc-sprayed room (31 dB at 100 KHz to 71 dB at 2.4 GHz).

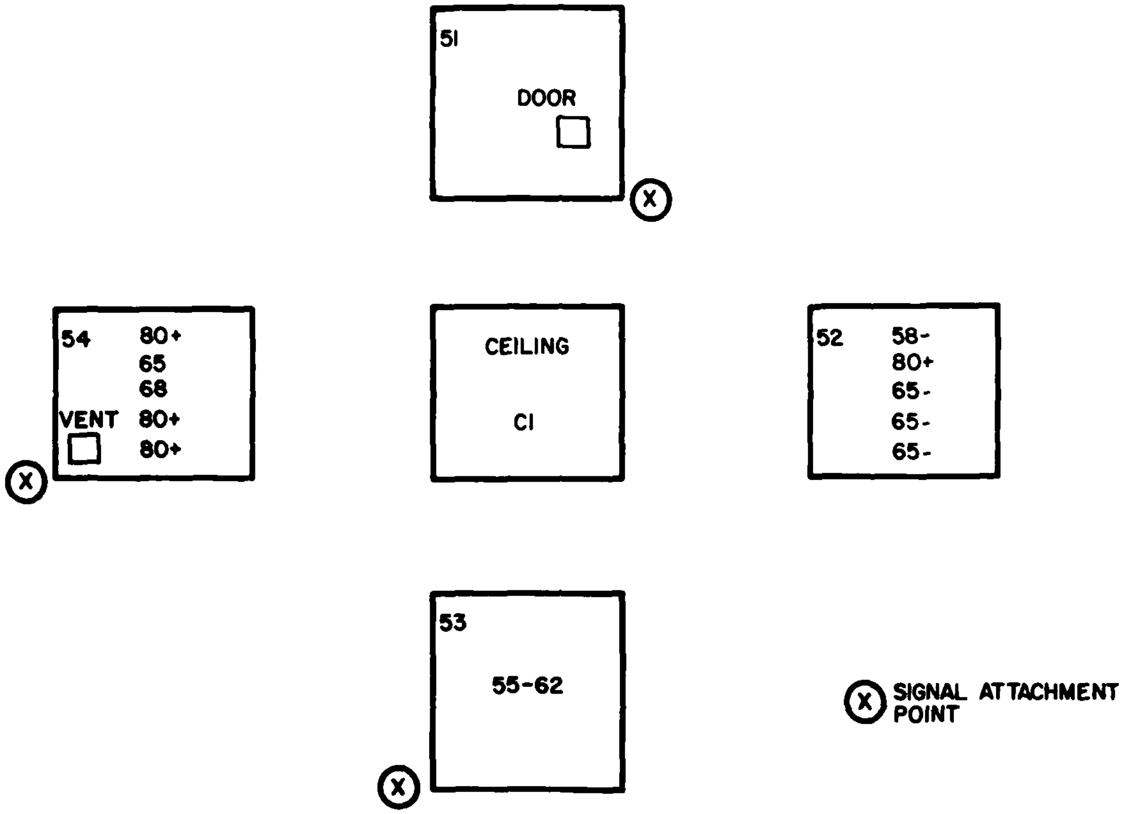

Figure 10. Shielded enclosure leak detector ("sniffer") measurements of copper-foil-covered room (general layout).

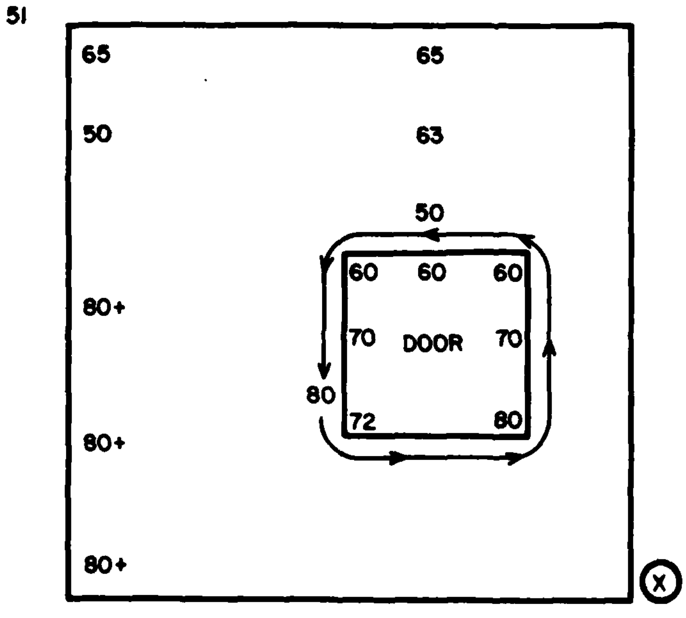

Figure 11. "Sniffer" readings of Side 1 of copper-foil-covered room.

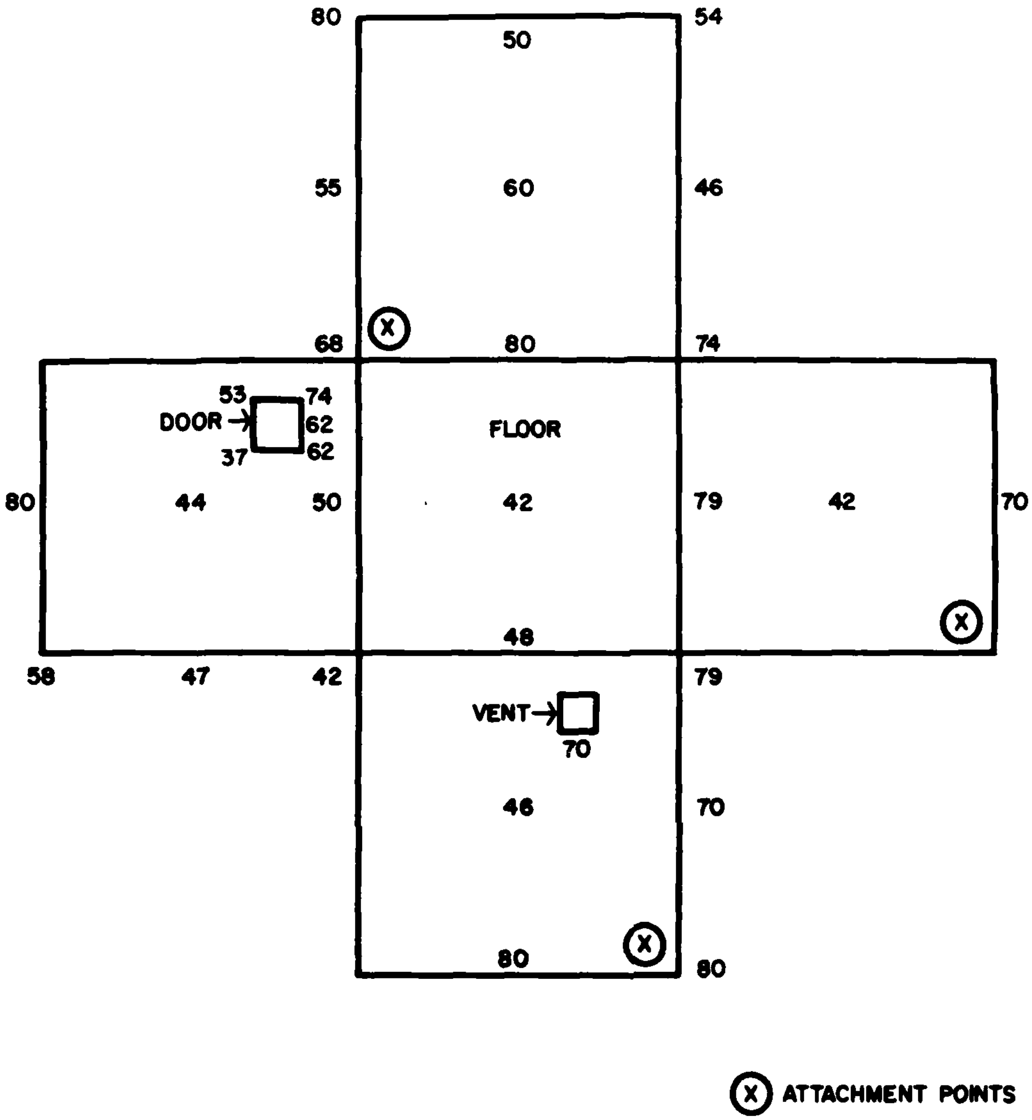

Figure 12. Shielded enclosure "sniffer" readings of zinc arc-sprayed room.

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